

SCET for jet physics in the vacuum and the medium

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Abstract

In this plenary talk I discuss soft-collinear effective theory (SCET) as a framework for precision QCD phenomenology. Emphasis is placed on jet and heavy flavor observables accessible at current and future collider facilities. One of the principal challenges that calculations of hard probes in heavy ion reactions face is the ambiguity associated with the implementation of medium-induced radiative effects. I demonstrate how extension of SCET to describe parton propagation in QCD matter has helped quantify and reduce the theoretical uncertainty in jet quenching calculations.

Keywords: SCET, SCET_G, jets, heavy flavor, heavy ion collisions

1. Introduction

The purpose of these proceedings is to highlight selected recent results obtained in the framework of soft-collinear effective theory (SCET) [1, 2] and its extension to describe jet propagation in a background QCD medium via Glauber gluon exchange [3, 4]. Emphasis is placed on observables that illustrate the gains in precision from higher-order calculations and resummation. Observables of direct relevance to experiments at current and future high-energy nuclear physics facilities such as the Relativistic Heavy Ion Collider (RHIC), the Large Hadron Collider (LHC) and an Electron Ion Collider (EIC) are given priority. Results for jets and heavy flavor, strictly within traditional pQCD, are covered elsewhere and summarized in [5]. Experimental results are collected in [6].

2. SCET for jet physics in the vacuum

Soft-collinear effective theory has emerged as a new tool to address hard large Q^2 processes in lepton-lepton, lepton-hadron, and hadron-hadron collisions. Together with QCD factorization, which has been proven in this framework for a number of processes, it is especially useful in improving the precision of multi-scale calculations through the resummation of large Sudakov-type

logarithms. While initially a large body of work was dedicated to e^+e^- annihilation, recently there has been more focused effort toward processes of interest to LHC phenomenology and a future EIC.

As a first example we consider one inclusive jet production in deep inelastic scattering (DIS). The discussed observable is called 1-jettiness in DIS is defined by one jet and one beam axis

$$\tau_1 \equiv \frac{2}{Q^2} \sum_{i \in X} \min\{q_B \cdot p_i, q_J \cdot p_i\}. \quad (1)$$

Here q_B, q_J are lightlike four-vectors along the beam and jet directions. In terms of collimated parton shower structures, this is similar to 2-jettiness in e^+e^- (two jets in the final state) and 0-jettiness in pp (Drell-Yan). This event shape distribution has been calculated over the past 15 years with increasing theoretical precision from next-to-leading logarithmic (NLL) accuracy to next-to-next-to-next-to-leading (N³LL) logarithmic accuracy [7, 8, 9, 10]. An example of these improvements can be seen in Fig. 1¹. The uncertainty band is reduced from a factor of few to just a few percent. The kinematics is chosen to be representative of HERA measurements. These improvements can help test the universality of non-perturbative effects and extract the strong

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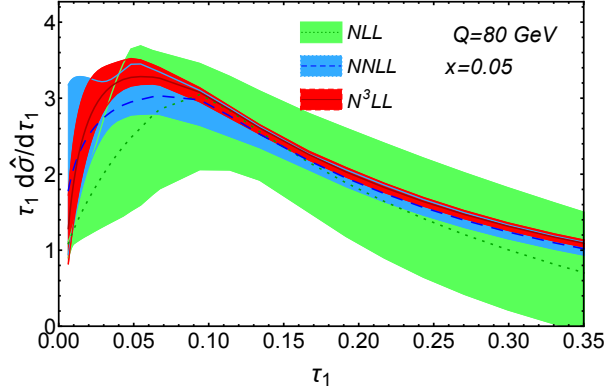


Figure 1: Example of perturbative convergence of the 1-jettiness for NLL, NNLL, N^3LL resummation at $x = 0.05$ and $Q = 80$ GeV [10].

coupling constant at the Z^0 pole, $\alpha_s(m_Z)$. The development of this technology is also useful in broadening the scope of the future EIC physics program.

In the past few years there has been a proliferation of NNLO calculations for the LHC (H +jet, W^\pm/Z^0 +jet, etc). While NLO $V+N$ jet calculations, that can also be matched to parton showers, generally work well, there are notable exceptions. One such example is the scalar momentum sum p_T distributions of associated jets. One of the main challenges in such calculations is the treatment of infrared (IR) singularities. Generally, two approaches are commonly adopted, local and non-local subtraction schemes. SCET, and the N -jettiness variable has found a novel application in a non-local subtraction scheme [11, 12]. At NNLO the cross section can have up to two additional partons in the final state and can be expressed schematically as follows

$$\begin{aligned} \sigma_{NNLO} = & \int d\Phi_N |\mathcal{M}_N|^2 + \int d\Phi_{N+1} |\mathcal{M}_{N+1}|^2 \theta_N^< \\ & + \int d\Phi_{N+2} |\mathcal{M}_{N+2}|^2 \theta_N^< + \int d\Phi_{N+1} |\mathcal{M}_{N+1}|^2 \theta_N^> \\ & + \int d\Phi_{N+2} |\mathcal{M}_{N+2}|^2 \theta_N^>. \end{aligned} \quad (2)$$

Here, $\theta_N^>$ and $\theta_N^<$ represent a cut for a small value of the N -subjettiness variable τ_N . Below τ_N one uses the factorization theorems of SCET to evaluate the cross section. If the cross section is expanded to the appropriate fixed order it will reproduce the NNLO result. Above τ_N the fixed order calculation works well, in particular one needs the results with $N+1$ and $N+2$ jets. An example of the calculation of the scalar sum of transverse momenta of jets associated with a Z^0 boson is shown in

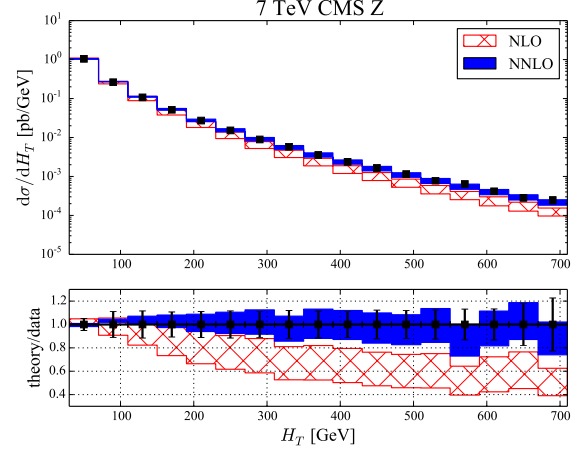


Figure 2: The scalar sum of jet transverse momenta distribution in Z +jet processes measured by CMS. The ratio of the NLO and NNLO predictions to the measured data is shown [12].

Fig. 2². The theoretical uncertainties are reduced and there is much better agreement between theory and experiment.

A noteworthy development in the past year was the development of SCET resummation for semi-inclusive jet observables. For jet production, logarithms of the jet radius parameter arise. When the jet radius R is small, such logarithms can become large and require resummation. It was recently shown that when the out-of-cone radiation is not power suppressed, $\mathcal{O}(\Lambda/E_J)$, these terms are of the form $(\alpha_s \ln R)^n$ [13, 14, 15, 16]. The new semi-inclusive jet functions follow DGLAP-type evolution equations [17]. For more details see the contribution by Ringer [18].

3. SCET for jet physics in a QCD medium

An effective field theory (EFT) for hard processes in heavy ion collisions can be constructed by coupling the jets to the QCD medium by off-shell t -channel Glauber gluon exchanges with momentum scaling $q \sim (\lambda^2, \lambda^2, \lambda)$, where λ is a small parameter. Building upon the soft-collinear effective theory of jet production [1], the collinear quark-Glauber and collinear gluon-Glauber sectors of the extended theory SCET_G were derived in [3] and [4]. In this background field approach, the properties of the QCD medium that determine the jet-medium interactions enter the potential that sources the Glauber gluons and first applications discussed the transverse momentum broadening of

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jets [3, 4, 19]. A critical step that enables calculations of parton shower modification in strongly-interacting matter and applications to jet quenching phenomenology beyond the traditional energy loss approach is the derivation of the all four splitting functions $q \rightarrow qg$, $g \rightarrow gg$, $g \rightarrow q\bar{q}$ and $q \rightarrow gq$ to first order in opacity [20]. The effect of correction that arise from the finite parton scattering kinematics, branching kinematics, and recoil of the constituents of the QCD medium has been studied.

One of the principal challenges that faces the theory of hard probes in heavy ion reactions is the unified description of vacuum and in-medium parton showers. The traditional energy loss approach relies on more than two decades of theoretical and phenomenological studies. In contrast, the implementation of the medium-induced parton branching requires new strategies and techniques, some of which have been developed in the context of high energy physics. The benefits of such advances, however, cannot be understated. Significant improvements in the precision of heavy ion phenomenology from resummation and higher order corrections [21] are expected. As a first example, the corrections to the DGLAP evolution equations [17] in the QGP were considered, with SCET_G splitting kernels as input [22]. This allowed us to quantify the uncertainties due to the implementation of the in-medium modification to inclusive hadron production. Predictions for light hadron suppression [23] are in excellent agreement with preliminary CMS results [24].

To extend the in-medium EFT approach to the heavy flavor sector, one needs to couple the charm and beauty quarks to the QCD medium. This was recently done in [25] and reported at this conference by Ringer [18]. The SCET_M Lagrangian in the vacuum with quark masses was obtained in [26]. Introduction of heavy quark masses requires specific power counting, $m/p^+ \sim \lambda$ of the order of the small power counting parameter in SCET. This is also consistent with the power counting for the dominant transverse momentum component of the Glauber gluon exchange. Hence, to lowest order the new effective theory of heavy quark propagation in matter. SCET_{M,G} = SCET_M ⊗ SCET_G. The three splitting processes where the heavy quark mass plays a role, $Q \rightarrow Qg$, $Q \rightarrow gQ$ and $g \rightarrow Q\bar{Q}$, have been computed analytically to first order in opacity and evaluated numerically. Incorporating their contribution in a framework consistent with next-to-leading (NLO) calculation can be schematically expressed as

$$d\sigma_{\text{PbPb}}^H = d\sigma_{pp}^{H,\text{NLO}} + d\sigma_{\text{PbPb}}^{H,\text{med}}, \quad (3)$$

where $d\sigma_{pp}^{H,\text{NLO}}$ is the NLO cross section in the vac-

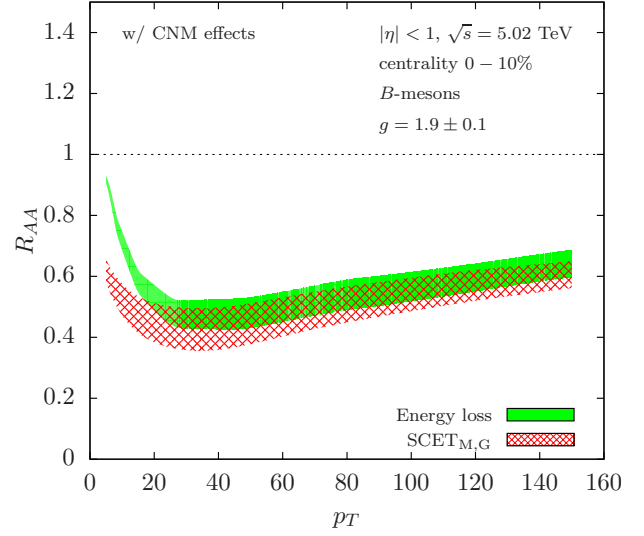


Figure 3: The nuclear modification factor R_{AA} for B^+ meson (right) production as a function of the transverse momentum p_T . Result obtained within the traditional approach to energy loss are compared to SCET_{M,G}-based calculations [25].

uum, and $d\sigma_{\text{PbPb}}^{H,\text{med}} = \hat{\sigma}_i^{(0)} \otimes D_i^{H,\text{med}}$ is the one-loop medium correction. Comparison of B-meson R_{AA} using the NLO framework of [27] and the fragmentation functions of [28] and the suppression obtained using the traditional energy loss approach is shown in Fig. 3. At high p_T the two approaches agree within the theoretical uncertainties. At lower p_T the significant gluon fragmentation contribution to open heavy flavor leads to values of R_{AA} that may be smaller by as much as 50%.

The transverse and longitudinal structure differences between the vacuum and in-medium parton showers can be clarified in considerable detail through studies of jets and jet substructure in proton and heavy ion collisions. Since jets are defined through a reconstruction algorithm with jet radius parameter R , the concept of energy loss can be generalized due to out-of-cone radiation [29]. More specifically, the medium-induced energy loss of a quark or gluon initiated jets is

$$\epsilon_i = \frac{2}{\omega} \left[\int_0^{\frac{1}{2}} dx k^0 + \int_{\frac{1}{2}}^1 dx (p^0 - k^0) \right] \int_{\omega x(1-x) \tan \frac{R}{2}}^{\omega x(1-x) \tan \frac{R_0}{2}} dk_{\perp} \frac{1}{2} \sum_i \mathcal{P}_{i \rightarrow jk}^{\text{med}}(x, k_{\perp}). \quad (4)$$

Here, R is the angular parameter used in the jet reconstruction, and R_0 is of $\mathcal{O}(1)$ in QCD, which sets the region of the use of collinear parton splitting functions. $\mathcal{P}_{i \rightarrow jk}^{\text{med}}(x, k_{\perp})$ are the medium-induced Altarelli-Parisi splitting kernels. With an emphasis on a the consistent

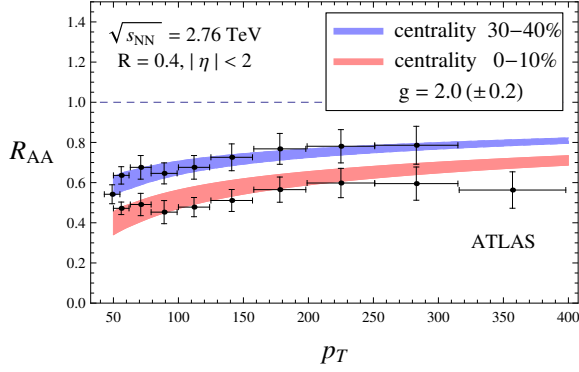


Figure 4: Calculations of the nuclear modification factor R_{AA} of inclusive jets as a function of the jet transverse momentum are compared to experimental data in central and mid-peripheral Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV at the LHC. Bands correspond to the theoretical uncertainty estimated by varying the coupling between the jet and the medium ($g = 2.0 \pm 0.2$) [29].

theoretical descriptions of hadron and jet observables in heavy ion collisions, the results presented in [29] include cold nuclear matter (CNM) effects and splitting functions used to evaluate light particle quenching. In Fig. 4 the suppression of jet production in central and mid-peripheral lead-lead collisions is compared to ATLAS experimental data [30].

The jet shape, a classic substructure observable, can give complimentary information on the in-medium parton shower. The integral and differential jet shapes are defined as follows

$$\Psi_J(r) = \frac{\sum_{i, d_{in} < r} E_T^i}{\sum_{i, d_{in} < R} E_T^i}, \quad \rho(r) = \frac{d}{dr} \Psi(r). \quad (5)$$

It was found that the non-trivial behavior of the jet shape modification is caused by both the different quark and gluon jet cross section suppressions and the jet-by-jet broadening. The cross section of gluon-initiated jets is more suppressed, which enhances the fraction of quark-initiated jets having a narrower energy profile. This causes the attenuation of the jet shape in the mid r region. On the other hand, the broadening of jets results in the enhancement of the jet shape near the periphery of the jet. The calculation provides for the first time a quantitative description of the jet shape modification in Pb+Pb collisions at the LHC [31], shown in Fig. 5.

Deeper inspection of jets has recently become possible [32]. In the context of heavy ion collisions, the groomed soft-dropped momentum sharing and angular separation distributions between the leading subjects inside a reconstructed jet are particularly interesting [33]. These observables are directly sensitive to the hardest

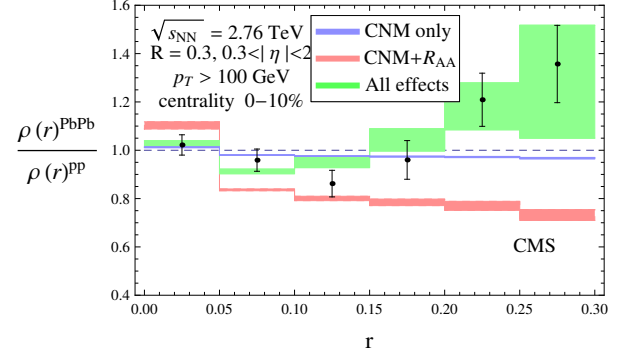


Figure 5: Theoretical calculations for the modification of differential jet shapes of inclusive jets in central Pb+Pb collisions at the LHC. The jet transverse momentum $p_T > 100$ GeV and pseudo-rapidity $0.3 < |\eta| < 2.0$. The coupling between the jet and the medium is fixed at $g = 2$.

branching in the process of jet formation and are an ideal tool to study the early stage of the in-medium parton shower evolution. To construct these variables one goes through the branching history of a shower, eliminating the soft branch at each step until

$$z_{cut} < \frac{\min(p_{T_1}, p_{T_2})}{p_{T_1} + p_{T_2}} \equiv z_g. \quad (6)$$

A further minimum angular separation restriction between the two branches $\Delta < \Delta R_{12} \equiv r_g$ is imposed, where ΔR_{12} is defined as the groomed jet radius r_g . Examination of the modification of the momentum sharing distribution $p(z_g)$ and the groomed radius distribution $p(r_g)$ distribution can shed light on the parton shower modification in heavy ion collisions. Specifically, one can select the jet transverse momentum and the angle between the two leading subjects, ensure large splitting virtuality and, consequently, a branching which happens shortly after the hard scattering in the QGP. The branching time, estimated as follows

$$\tau_{br}[\text{fm}] = \frac{0.197 \text{ GeV fm}}{z_g(1 - z_g)\omega[\text{GeV}] \tan^2(r_g/2)}, \quad (7)$$

suggests that for typical jets with $\omega = 2p_T = 400$ GeV, $r_g = 0.1$ and $z_g = 0.1$, the branching time $\tau_{br} < 2$ fm. This selects early splitting process inside the QGP of size ~ 10 fm created in Pb+Pb collisions at the LHC. The modification of the momentum sharing and angular separation distributions in lead-lead relative to proton-proton collisions is evaluated using the leading-order medium-induced splitting functions obtained in the framework of soft-collinear effective theory with Glauber gluon interactions [20]. Qualitative and in

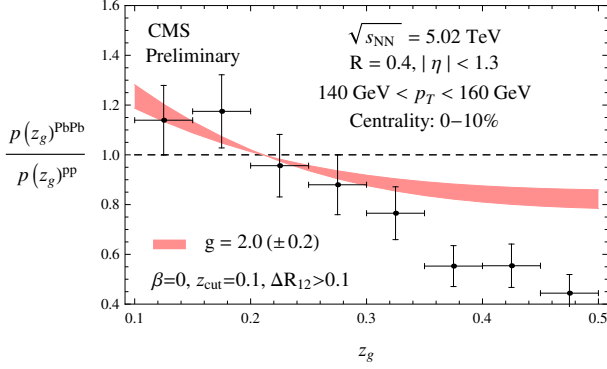


Figure 6: Calculations and preliminary CMS data for the ratio of momentum sharing distributions of inclusive anti- k_T $R = 0.4$ jets in central Pb+Pb and p+p collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The band corresponds to the theoretical uncertainty estimated by varying the coupling between the jet and the medium ($g = 2.0 \pm 0.2$) [33].

most cases quantitative agreement between theory and preliminary CMS measurements [6] is observed. The medium enhances the asymmetric branching and one example in central heavy ion reactions at the LHC is shown in Fig. 6 for the jet momentum range $140 \text{ GeV} < p_T < 160 \text{ GeV}$. The variance at $z_g \sim 0.5$ between data and theory disappears at higher p_T and less central collisions. The STAR collaboration at RHIC did not see strong groomed jet modification at lower transverse momenta.

Finally, it is important to note that in the soft gluon emission limit only two of the four medium-induced splitting intensities survive $q \rightarrow qg$, $g \rightarrow gg$. This allows for a standard energy loss interpretation of jet quenching, i.e. leading partons lose energy through non-Abelian bremsstrahlung and flavor changing processes are suppressed [20]. In this limit, using vector boson (γ , Z^0) tagging, more accurate constraints can be placed on jet energy loss in comparison to inclusive jet, and even di-jet measurements. Convenient variables that encode such information are the tagged jet momentum asymmetry A_{JV} and momentum imbalance X_{JV} defined as

$$A_{JV} = \frac{p_{TJ} - p_{TV}}{p_{TJ} + p_{TV}}, \quad X_{JV} = \frac{p_{TJ}}{p_{TV}}. \quad (8)$$

Complete characterization of the quenching of photon-tagged jets, for example, requires measurements of the double differential distribution and is not possible at present due to limited statistics. Their momentum imbalance can be obtained as follows

$$\frac{d\sigma}{dX_{JV}} = \int_{p_{TJ}^{\min}}^{p_{TJ}^{\max}} dp_{TJ} \frac{p_{TJ}}{X_{JV}^2} \frac{d\sigma[X_{JV}, p_{TJ}(X_{JV}, p_{TJ})]}{dp_{TJ} dp_{TV}}, \quad (9)$$

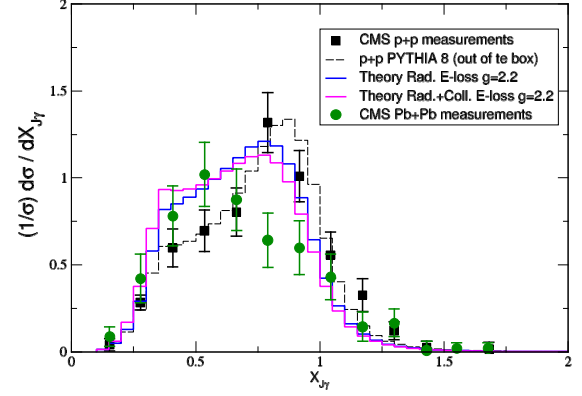


Figure 7: The momentum imbalance distribution X_{JV} in proton and heavy ion collisions at center-of-mass energy 2.76 TeV is compared to preliminary CMS data. Theoretical calculations of the momentum imbalance shift from p+p to Pb+Pb are performed in the energy loss limit [34] for 0-30% central collisions.

where the experimental transverse momentum cuts determine the range of X_{JV} and influence its distribution. The normalized momentum imbalance distribution $(1/\sigma)d\sigma/dX_{JV}$ is given in Fig. 7. Theoretical results [34] use Pythia8 to simulate the p+p baseline. Radiative and collisional energy losses are further included in the description of the photon-tagged jet momentum imbalance in central Pb+Pb collisions at the LHC. Preliminary CMS data is also included and the downshift in the X_{JV} distributions from p+p to Pb+Pb is qualitatively consistent with theoretical expectations with new results from ATLAS and CMS expected to appear soon [6].

4. Conclusions

This plenary talk highlighted selected recent results obtained in the framework of soft-collinear effective theory and its extension to include Glauber gluon interactions between jets and strongly-interacting matter. Precision calculations of jet production in DIS can help constrain the strong coupling constant and parton distribution functions from existing HERA and future EIC data. In hadronic collisions, tagged jet cross section at NNLO set a remarkably accurate baseline for the study of the effects of the QCD medium in heavy ion collisions. Small jet radius resummation for inclusive jets and jet substructure was recently achieved in SCET. An important development for ultra-relativistic nuclear collisions, seeded by SCET_G, is the unified treatment of vacuum and medium-induced parton showers. The advancements in theory include medium-modified

evolution, an extension of the effective theory of jet propagation in QCD medium to heavy quarks, and a consistent framework to calculate hard processes in heavy-ion collisions at NLO. Significant progress has been achieved in the description of inclusive and tagged jet cross sections and jet substructure in heavy ion collisions.

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